Lead-Bismuth Eutectic (LBE) Materials Test Loop (MTL) Test Plan v2.0

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1. INTRODUCTION AND BACKGROUND

The U.S. DOE Advanced Accelerator Applications (AAA) Program aims to develop an Accelerator-Driven Test Facility (ADTF) that provides a world-class test facility to assess technology options for the transmutation of spent nuclear fuel and waste, and provide a test bed for advanced nuclear technologies and applications.

The development and testing of a high power high flux spallation target as the external neutron source for the subcritical blanket is critical for ADTF and future Accelerator-driven Transmutation of Waste (ATW) applications.

Lead-bismuth eutectic (LBE) emerged as a leading candidate for high-power spallation targets[1]. LBE has exceptional chemical, thermal physical, nuclear and neutronic properties well suited for nuclear coolant and spallation target applications[2]. In particular, LBE has a low melting temperature (123.5°C) and very high boiling temperature (~1670°C), is chemically inert and does not react with air and water violently, and can yield close to 30 neutrons per 1 GeV proton. However, LBE corrosion has long been recognized as a leading obstacle to its nuclear applications, and LBE has not been used in high-power spallation targets.

The LANL ATW and DOE AAA programs have invested in developing LBE technology for spallation target and nuclear coolant applications since 1997[3]. Currently we have one standby LBE hydraulic test loop, one LBE material and thermal hydraulic test loop (MTL) under construction, an experiment to develop oxygen sensor and control. We participated in the ISTC project #559 in which a 1-MW LBE spallation test target[4] was designed and fabricated in Russia, and was assembled and tested out-of-beam. We have had several completed research contracts in LBE technology transfer and support R&D with the Institute of Physics and Power Engineering (IPPE), Obninsk, the leading Russian institute in LBE nuclear coolant technology. We have established a solid foundation for LBE technology transfer and development at LANL.

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[1] "A Roadmap for Developing Accelerator Transmutation of Waste (ATW) Technology – A Report to Congress", DOE/RW-0519, October, 1999.

[2] E. O. Adamov and V.V. Orlov, "Nuclear Development on the Basis of New Concepts of Nuclear Reactors and Fuel Cycle", proceedings of Heavy Liquid Metal Coolants in Nuclear Technology (HLMC-98), Obninsk: SSC RF – IPPE, 1999, Vol.1, 24-31, and references therein.

[3] N. Li, "Lead-Bismuth Eutectic (LBE) Coolant Technology Development at Los Alamos National Laboratory", LANL technical report, LA-UR-00-5129 (2000).

[4] E. I. Yefimov *et al*. "Target Circuit TC-1 – Explanatory Report", ISTC#559 program report, SSC RF IPPE and RDB "Gidropress", 1998.

In the meantime, the international community of ADS (accelerator-driven systems) has placed significant resources into the development of LBE technology as well. There are European, Japanese, South Korean LBE programs that are larger or comparable to our LBE effort. We have maintained informal contact and collaboration with many of these programs through conferences, emails and visits.

LBE has also received resurgent interest worldwide as a candidate for nuclear coolant applications in advanced reactors that are simple, modular, passively safe and proliferation resistant, with long-lasting fuels. Currently, there are efforts for reactor design or material compatibility study at national laboratories, universities and many international organizations. There is an informal information exchange network for researchers interested in the LBE technology.

Despite the considerable progress made in developing the LBE technology, successful deployment of LBE targets will require additional testing. The testing program includes (a) out-of-beam tests, and (b) in-beam (irradiation) tests.

The Materials Test Loop (MTL) is an essential part of the out-of-beam testing program in the U.S. MTL is a major step toward demonstrating the use of LBE on a scale representative of MW level spallation targets. We will implement and test the performance of the oxygen control technique to reduce LBE corrosion[5], test candidate materials for target use, and in general acquire the experience to design, construct and operate an LBE system. Without such loop testing to clearly understand the performance of materials and components, and the operational complexity, it is not feasible to conduct an in-beam test of a prototypic spallation target. While some of the irradiation effects (such as the effect of spallation products on oxygen control) may be tested in the MTL using surrogates, the ultimate verification of the technology will require an in-beam testing under representative irradiation environment.

MTL may benefit other US DOE programs, such as the Generation IV Nuclear Energy Systems Initiative[6] and spallation neutron source development for research applications.

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[5] N. Li, "Active Control of Oxygen in Molten Lead-Bismuth Eutectic Systems to Prevent Steel Corrosion and Coolant Contamination", LANL technical report, LA-UR-99-4696 (1999), accepted for publication in J, Nuc, Mat..
X. Y. He, N. Li, A. Smith and M. Mineev, "A Kinetic Model for Corrosion and Precipitation in Non-isothermal LBE Flow Loop", J. Nuc. Mat. 297 (2001) 214-219.

[6] See http://gen-iv.ne.doe.gov/.

MTL and the associated expertise and experience can also play an important role in the AAA Program international collaborations. It complements and supplements other LBE development programs, such as the German KArlsruhe Lead LAboratory (KALLA) and the EU-led MEGAPIE (MEGAwatt Pilot Experiment) to develop and demonstrate a MW level LBE spallation target at the Paul Scherrer Institute (PSI). We will coordinate our test experiments with these programs.

2. OBJECTIVE AND REQUIREMENTS

2.1 Objectives

MTL is a facility designed to test the safe operation of a medium-size, forced-circulation LBE system with representative thermal hydraulic conditions (as in spallation target and/or transmutation blanket systems), to perform corrosion tests, and to develop candidate materials with oxygen control (and related probes and control systems). MTL can also be used to study the performance of our design, engineering and construction practices, component selection, and safety procedures, prior to deploying a spallation target in the beam.

The near term objective of the MTL is to support the engineering design and development (ED&D) efforts for the ADTF. The longer term objective is to enhance the LBE technology data-base in support of the spent nuclear fuel transmutation and advanced nuclear reactor applications.

2.2 Technical Performance

The specifications of MTL are set and modified to simulate representative thermal hydraulic conditions of spallation target and blanket systems, with sections of well-conditioned flow for materials testing. Sizing is based on two considerations: facility constraints and resources, and practical implementation of the largest possible loop to establish LBE technology feasibility for transmutation applications. Other support R&D (U.S. laboratories and International collaborations) provides the needed technological underpinning.

MTL-R-00   **The design lifetime must be $\geq$ 3 years.**

> **Basis:** The design lifetime provide sufficient time to perform meaningful material testing without long interruptions caused by component failure. The components that require frequent replacement should be easily replaceable to minimize the interruptions of the testing. Also, reasonable considerations must be given to the lifetime extension beyond 3 years during the design phase.

MTL-R-01   **LBE flow velocity up to 3 m/s in the test section.**

Basis: Russian LBE nuclear coolant technology development (and other technical data) indicates that 2-3 m/s represents a possible boundary for the onset of erosion and/or erosion/corrosion for nominally corrosion resistance alloys (e.g.EP823). Russian reactor designs (including the IPPE/Gidropress design of a 1-MW LBE spallation neutron test target) use 2 m/s for the upper limit of LBE coolant flow in core (or active target volume). With a typical sizing of the test section piping of 1" ID, the Reynolds number Re = Vd/ν =3.6E5. So the flow from 2m/s down to ~1cm/s is turbulent, well-mixed, and the corrosion test results may be scalable with flow velocity.

For other thermal hydraulic experiments in the future (e.g. heat transfer from geometry of critical components, such as target windows and/or transmutation assemblies; onset of erosion and/or erosion/corrosion; flow field measurement and diagnostics development etc)

MTL-R-02   LBE volume flow rate up to 15 m^3/h.

Basis: This volume flow rate is prototypic of a 1 MW LBE spallation target, with a temperature difference of 100ºC. The capacity is intended for future thermal hydraulic experiment and is not necessary for near term test operations and materials tests. The requirement is secondary to the flow velocity and temperature requirements.

MTL-R-03   Maximum loop temperature is 500°C with a minimum temperature difference of 100°C along the loop

Basis: The Russian experience and some recent test results (including the LANL-IPPE contract to test 5 US steel specimens) indicate that LBE systems operating within the range of 300 - 550ºC are feasible with oxygen control and some modification or improvement of available nuclear materials (austenitic steels such as 316/316L and ferritic/martensitic steels such as HT-9)[7].

For LBE spallation targets, there is also the desire to operate in the range of intermediate temperatures to lessen the effect of radiation induced embrittlement of F/M steels, while not losing substantial mechanical strength at higher temperatures.

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[7] "Results of Corrosion Tests of 316, 316L, T-410, HT-9 and D-9 Steels – Final Technical Report", LANL Contract #H12030008-35, performed by SSC RF IPPE (Russia), October 2000.

To test the extreme limits, it is also desirable to achieve 550°C max and 200°C difference for blanket systems and accelerated corrosion testing.

MTL-R-04   LBE purity must be higher than 99.5%.

Basis: For reducing impurities caused corrosion, mass transfer and precipitation, and, in case of nuclear activation, activation by irradiation, there is a limit to admissible levels of impurities. We do not have a database to specify that but can infer from the limited Russian literature[8] what this might be.

It appears that typical impurities in LBE from US suppliers can be lower than that are required of a nuclear coolant, with the exception of antimony, arsenic, tellurium and zinc. This requirement will have to be further refined as we learn more from the operation of MTL and other supporting experiments.

MTL-R-05   Oxygen level in LBE must be measurable and controllable.

Implementation must be able to measure oxygen at levels of 10 ppb to a few ppm mass concentrations in LBE, from 350 - 550°C. Adjust and control its level via direct injection of oxygen or hydrogen gas mixtures into LBE, or the use of hydrogen/steam mixtures in the cover gas.

Basis: This is the key technological requirement. The technique is based on the Russian technology[9]. We have achieved significant understanding of the underlying mechanisms and requisite instrumentation (oxygen sensors) and control system, through technology transfer and our own development[10].

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[8] V. V. Orlov *et al*. "Lead Cooled Fast Reactor – New Nuclear Technology for the Future Large Scale Nuclear Power", Russia.

[9] B. F. Gromov *et al*. "The Problems of Technology of the Heavy Liquid Metal Coolants (Lead-Bismuth, Lead)", proceedings of Heavy Liquid Metal Coolants in Nuclear Technology (HLMC-98), Obninsk: SSC RF – IPPE, Vol.1, 87-100 (1999).

[10] N. Li, "Active Control of Oxygen in Molten Lead-Bismuth Eutectic Systems to Prevent Steel Corrosion and Coolant Contamination", technical report, Los Alamos National Laboratory, LA-UR-99-4696 (1999), accepted for publication in J. Nuc. Mat.

We developed a working prototype of Bi/Bi-oxide reference electrode, yttria-stabilized zirconia solid electrolyte oxygen sensor based on automobile sensors[11]. The gas control system will be first implemented with direct injection of oxygen and hydrogen gas mixtures in a bypass loop.

MTL-R-06   MTL must be capable of natural convection velocities of 10-20cm/s.

Basis: In addition to demonstrate, measure and compare natural convection flow in MTL, such flow may be used for long term materials test without kinetically energized component (the pump) and without attendance (safety advantage).

It may also be important to study the coolant chemistry (esp. oxygen control) in natural convection flow since there will be no impeller to break up and mix gas injections. This assumes that there might be applications for natural convection only or hybrid flow LBE systems in spallation targets and transmutation blankets. For this configuration, one alternative approach to oxygen control is to use the cover gas rather than direct injection. This requirement needs further refinement as we learn more from MTL operation.

MTL-R-07   Configuration and components must provide flexibility for materials and thermal hydraulic testing.

Basis: The loop needs to be re-configurable (e.g. with valves) for corrosion tests and thermal hydraulic experiment; placement of heaters and heat exchanger should allow significant natural convection (~20 cm/s in the test section). Sections of loop should allow for extraction for surveillance and replacement easily. Components, especially the pump, should allow ample margin for the stated technical performance.

MTL's drive and heater/HX capacity should have the capability for future experimental use beyond immediate needs. Since construction of other loops is unlikely given resource and space constraints, MTL will need to be versatile.

Since large LBE-cooled systems will likely use sump pumps, and we have experience in the first test loop, we will continue to use a sump pump for the drive and as a test

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[11] N. Li, "Lead-Bismuth Eutectic (LBE) Coolant Technology Development at Los Alamos National Laboratory", LANL technical report, LA-UR-00-5129 (2000).

component. EM pumps have advantages for compact systems, but they suffer low efficiency, high cost and very difficult short-term availability in US.

MTL-R-08   All parts in contact with LBE shall be made of 316, 316L or dual certified 316/316L stainless steel.

Basis: We know from our understanding of the LBE corrosion mechanism and the positive Russian experience with alloys of similar composition that 316 SS can be used for extended periods of time, especially if we avoid reducing cover gas environment (even without oxygen control), and keep the complex and difficult or expensive-to-replace components in contact with LBE to below 450°C. High temperature parts should be simple and easily replaceable.

IPPE completed a LANL-IPPE contract to test 5 US steels in an oxygen control LBE loop at temperatures of 460°C and 550°C, for time intervals of 1000, 2000 and 3000 hours. The dual certified 316/316L showed sufficient corrosion resistance, forming a good protective oxide film and showing no liquid metal corrosion[12].

Although LBE systems are low-pressure systems, the thermal stress in the piping system and the vessels may require mitigation measures to keep it within acceptable limits. Design will comply to ASME codes.

Note that, in cases of difficult availability of parts, substitute with Fe alloys containing sufficient Cr, but not with Ni-based alloys.

MTL-R-09   Data acquisition and control must be automated.

Basis: Data acquisition, electrical, thermal (heaters) and emergency response valves, and shutdown procedures should be automated. Configuration valves, variable heat exchanger, cooling water, gas and ventilation systems need not be automated. Pump automatic restart, if available, should be disabled.

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[12] "Results of Corrosion Tests of 316, 316L, T-410, HT-9 and D-9 Steels – Final Technical Report", LANL Contract #H12030008-35, SSC RF IPPE, October 2000.

MTL's basic operation, including preheating, temperature monitoring and modulation, emergency responses (e.g. drainage of LBE from the loop), and other repetitive procedures during normal operation should be automated. However, the testing nature of the facility should allow for flexibility and manual intervention, without jeopardizing the safety envelope.

2.3 Safety Performance

MTL has to comply with all relevant DOE/Laboratory regulations and safe work practices. It is, however, a test facility that will implement some unique features that only the operation of MTL itself will prove. Plausible accident scenarios will be considered to achieve no lead contamination beyond the facility boundary and no lead oxide release beyond the building ventilation system with HEPA filters in place.

MTL-R-10   Operator training must comply with ISM; i.e. all operations must comply with all relevant Laboratory regulations and policies, especially with lead awareness training.

> **Basis:** Lead hazard and control is well known due to the extensive industrial experience. There are also a set of comprehensive regulations and corresponding Laboratory training. It is absolutely essential to demonstrate that operating a medium to large-scale LBE facility can be safe, and unforeseen events of deviation during operation due to the development and testing nature of this operation will not harm the personnel and environment.

MTL-R-11   Structures must protect personnel and environment.

> **Basis:** No collapse or beyond design specified deformation of the support structures, and no catastrophic breaking of the LBE flow piping system should occur during normal operations or operational transients.

> The enclosure must withstand a design basis earthquake corresponding to a Performance Category 1 (PC-1) seismic event. The vessels must be built to ASME Boiler and Pressure Vessel Code.

The support structure for the loop and the platform for personnel access cannot fail under normal circumstances to guarantee personnel safety. It has to be seismic proof based on DOE facility requirements and the Uniform Building Code.

MTL uses many graphite gaskets for seals, flanges, bellow-stem valves, and welds for construction and assembly. Because there are no other economic and technically feasible methods of testing components and construction practices, it is more reasonable to assume that some might fail. Therefore, the design must ensure that no catastrophic consequences will follow, and that repair and mitigation measures can be carried out and implemented safely.

MTL-R-12   Thermal, electrical and mechanical hazards must be mitigated and sufficient isolation and access control, adequate personal protection equipment must be available.

Basis: Most of the thermal, electrical and mechanical hazards are not unique to MTL and safety measures should be implemented during construction and assembly.

However, the relatively constricted access of the lower level of MTL (heaters, bypass loop with oxygen control, melt tank and the drainage valves) requires procedural mitigation measures.

MTL-R-13   Chemical hazards must be contained.

Basis: Lead and lead oxide contamination in the surrounding air volume and surfaces, and release into the environment should be kept well below the DOE/Laboratory allowable limits.

Lead oxide presents particularly dangerous hazardd to operators and other personnel in the vicinity. Containment of its release should start at the exit gas line of the loop before the exhaust gas enters the building ventilation system.

Materials Safety Data Sheets (MSDS) should be available for all liquid metals (Pb and Bi), possible oxides from operations, and reaction products from possible interaction with air and water.

2.4 Scheduling Priorities

MTL is capable of various system preparation, calibration and operation, corrosion and material compatibility, and thermal hydraulic experiments. The AAA program priority sets the test scheduling priority.

MTL-S-01   Component performance must be frequently monitored and analyzed

> **Basis:** With many parts (valves, flanges, oxygen and level sensors, pressure and temperature transducers, heaters, etc) in the loop, we will monitor and record the performance of components and design and engineering practices to obtain some statistics for future spallation target development.
>
> This is not a separate test operation but an integral part of MTL operation and surveillance. If visible degradation or failure of any components surfaces, we will stop ongoing MTL test operation and determine the most effective path for repair, replacement and mitigation to ensure the safe operation of MTL.

MTL-S-02   Initially, LBE system preparation, preconditioning, and calibration must be performed

> **Basis:** Regardless of what actual experiments will be carried out first, the loop and LBE coolant should be prepared and conditioned. The instrumentation, including the oxygen sensor and control system, the EM flow meter, will be calibrated.
>
> The preconditioning of the loop and LBE is essential for successful long-term safe operation of the facility.

MTL-S-03   Measurement and control of oxygen level in LBE must be fully functional prior to long-term testing.

> **Basis:** This is the critical technology implementation for MTL to demonstrate and improve. MTL-S-1 requires that this implementation work. It is singled out here to signify that if this aspect of MTL malfunctions or fails, we will not proceed with other tests until the problems are solved.

MTL-S-04   MTL must be set-up for stable and specified thermal hydraulic operation

   Basis: Specifically, this means the startup of heat exchanger and heaters to reach desired temperature and temperature differences at a given LBE flow rate.

MTL-S-05   MTL must be capable of performing long duration (> 1000 hr) materials corrosion testing

   Basis: This testing will last for up to 1000 hrs first, to verify the corrosion performance of target candidate materials (HT-9, 316/316L SS). We will do smaller time interval tests to find out more about the initial oxidation process. Longer time interval test will be pursued after operational and short-term tests are completed.

MTL-S-06   MTL must be capable of testing LBE coolant cleanup and restoration

   Basis: Spallation target operation will require replacing the window in 1-2 years time, but the rest of the system and the coolant should be reconditioned and reused.

MTL-S-07   MTL must be capable of thermal-hydraulic tests simulating spallation target operation

   Basis: There are certain flow distribution and heat transfer issues that are critical to safe and reliable operation of spallation targets. MTL is designed to have the capacity to perform thermal hydraulic tests to benchmark codes and verify design features.

   It is very useful to test some spallation product effects as well. Unfortunately, this will likely foul the LBE coolant (hydrogen injection may be carried out without compromising the lifetime of MTL). Thus, the major emphasis in testing the spallation product effects will be on controlled injection of hydrogen into the loop. Other options (if needed) will be pursued in small-scale experiments first before fouling the lead-bismuth in the loop.

3. DESIGN OF MTL

3.1 Introduction

The liquid lead-bismuth loop is an experimental installation built to study the thermal hydraulic and corrosive behavior of liquid lead-bismuth eutectic. It is a closed loop consisting of a pump, piping, heat exchangers, and tanks. The parts of the loop are discussed in detail in the following chapter.
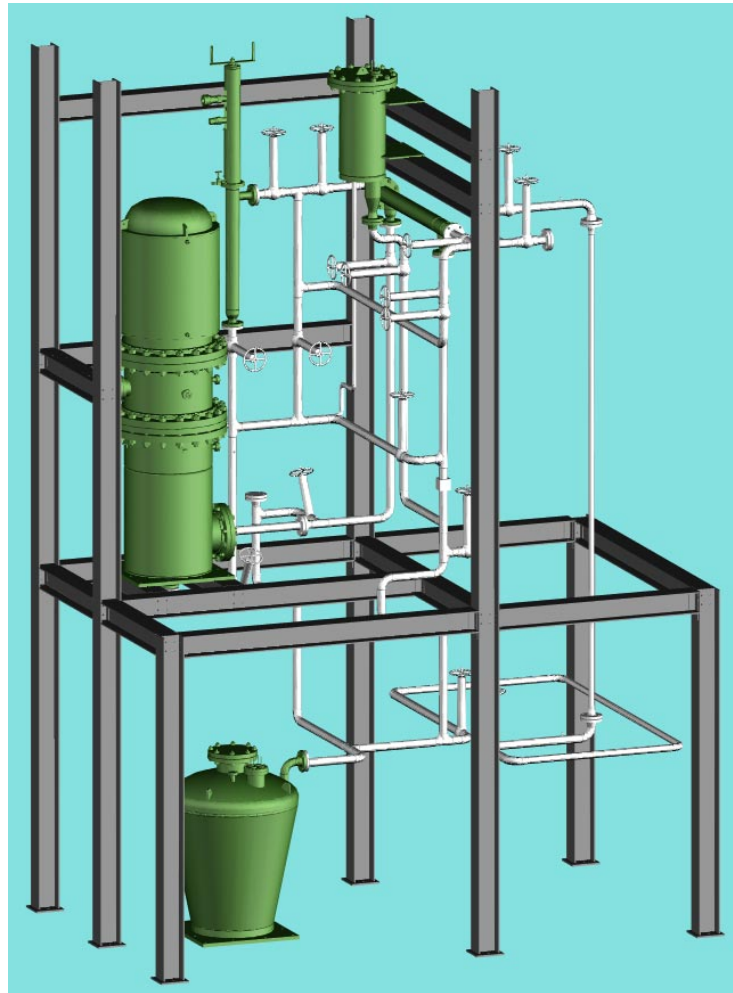
Figure 1. MTL layout (not final).

During operation lead-bismuth is melted in the Melt Tank and transferred by gas pressure into the Sump Tank. A centrifugal pump submerged in the liquid metal in the Sump Tank circulates the fluid through the loop. The pump has a head of 45feet at maximum power of 25hp, and its best efficiency point is 100 Gallons per minute (378.5l/min) at 25ft head. After leaving the sump

tank, liquid lead-bismuth travels up to the recuperator's shell side, where fluid's temperature is increased by 50^0C. A magnetic flow meter is placed on the long vertical pipe leading from the recuperator's shell side to the heated section at the bottom of the loop. Band heaters cover the next five horizontal tubes. There the fluid's temperature is raised another 50^0C. Then the liquid goes up through a1in vertical test section and through the tube side of the recuperator where its temperature is reduced by 50^0C. After leaving the recuperator, the fluid flows to the heat exchanger where its temperature is again reduced by 50^0C. The fluid leaves the heat exchanger through the bottom outlet, goes down through the vertical pipe, turns and returns to the sump tank through the bottom inlet.

All temperature changes shown in the previous paragraph are nominal for the design flow speed of 1m/s in the test section or about 5.9 kg/s mass flow rate.

3.2 Main Components

MTL-MT-1   Melt Tank

Before operation lead-bismuth ingots are loaded into a vessel called the melt tank. This tank is used to melt lead-bismuth and to collect it when the loop drains. It is shaped as a frustum of a cone with the larger diameter at the top. A hemispherical head tops the vessel. The melting tank is shown in Figure 2.

The melting tank is designed so that its conical part can completely contain 150% of the loop's total volume. The loop's volume is about 14191in^3 or 0.233m^3. Hence, the internal height of the conical part of the melting tank was calculated to be 33.5in and its diameters are 21.5in and 35in. The volume in the hemispherical head serves as gas plenum. Lead-bismuth

Figure 2. Melt Tank.

supply to the loop as well as drainage is realized through a 2in pipe that enters through the head 15in from the center axis and continues along the side of the melting tank down to the bottom. It has an elbow and a flange at the end that connects to the loop piping. It is a standard schedule 80 pipe, so its internal diameter is 1.939in, wall thickness is 0.218in and outside diameter is 2.375in.

There are three other openings in the head of this vessel. The largest is an 8in access opening in the center of the head. It is covered with a blind flange when the loop is operational. Level measuring rods are threaded through a blind flange that covers the 5in opening. The 5in tube that goes through this opening protects the level sensors from the lead-bismuth flow disturbances. The tube is perforated to provide fluid better access to the sensors. The 1.5 n opening serves as an access opening for thermocouples.

Twelve 8in by 33in flat panel heaters are arranged around the melt tank in a cylindrical frame. They can provide 45kW of heat, which is more than enough to melt the lead-bismuth bricks inside in about 50min. The heater will be modulated with a controller operated from a computer.

MTL-SP-1   Sump Tank

The pump comes from the vendor mounted on a 1in thick, 316 stainless steel support plate. The support plate is bolted to the I-beam support structure.

The pump shaft penetrates the support plate, with graphite packing at the penetration, and extends into the sump tank 36in, including the impeller housing. Above the support plate, the pump shaft extends through a bearing assembly to a shaft coupling, then to the pump motor. Because of the lack of adequate seal at the graphite packing around the pump shaft at the support plate penetration, it is necessary to fully enclose the pump motor as well as the pump sump so that equal pressure can be maintained on both sides of the support plate.

The entire enclosure consists of 3 separate vessels:

1.0 The sump,
2.0 A water cooled motor cover,
3.0 An intermediate vessel joining the sump and the motor

   cover (motor housing base).

All these parts are made of 316L stainless steel.

Figure 3. Sump and motor enclosure.

The sump tank consists of a welded pipe cylindrical shell, a flat 2in bottom support plate welded to the shell, and a rotatable flange to couple the support plate to the intermediate vessel. The sump wall thickness is 0.5in and outside diameter is 24in and it consists of a pipe welded to a standard stub end for flange attachment.

The sidewall has a large penetration near the bottom for the pump discharge pipe (see Figure 3). The penetration consists of a short stub of 10in schedule 40 pipe, with welded 10in 150lb. slip-on flange. This pipe has outside diameter of 10.75in and wall thickness of 0.365in. The pump outlet is connected to the bellows that is inside of this discharge pipe.

Near the top of the sump tank there are two penetrations for instrumentation and gas lines. The opening with1-1/5in outside diameter and 0.188in wall tube connects to a gas line that is used to evacuate and to pressurize the sump tank. This opening is directly above the large pump outlet flange. In Figure 3 it is shown covered with a blind flange. The second opening is finished with a 1in schedule 40 pipe that connects to a 1in pipe connecting the sump tank and the calibration tank. This pipe allows the pressure within the two tanks to be the same and it can serve as an overflow pipe for the calibration tank as well.

The bottom plate is 2in thick and has a penetration in the center for a loop return line. Loop return line is a 2in schedule 40 pipe as most of the other piping in the loop. This pipe outside diameter is 2.375in and its wall thickness is 0.154in. There is a 300lb 2in flange that connects the loop and the sump pipes.

The pump motor enclosure is shown on Figure 3 at the top. It is made of 316L stainless steel. It is a cylinder with a standard hemispherical head welded to it. The cylindrical part has a double wall to provide for cooling water flow around the motor enclosure. It is called a water jacket. Standard pipe fittings at 4 places allow for the water flow into and out of this jacket. The water is nominally at room temperature and will be provided from the building water system. Bottom end of the motor enclosure will mate with the intermediate vessel via a fixed (welded), 150 lb. lap joint flange.

The intermediate vessel, also called motor cover base, is shown in the middle of Figure 3. It is 18 inches high, with a fixed (welded), lap joint flange (150 lb.) on each end. The shell of this vessel is schedule 20 24" pipe with outside diameter of 24in and wall thickness of 0.375in. This vessel has four penetrations. Two of them 1.5in holes with welded 1.5in diameter tube, 0.065in wall. The forth is a 5in tube, 0.12in wall thickness. It is covered with a blind flange that is 0.84in thick and has four electrical connections bolted through it. These connections are used to

feed through the signal from the level sensors in the sump tank. The other openings can be used for electrical feed-throughs or for gas lines connections.

MTL-CT-1   Calibration Tank

The calibration tank is used for magnetic flow meter calibration. This tank consists of a welded pipe cylindrical shell, a flat bottom support plate, welded to the shell, and a welded flange ring with blind flange at the top for closure.

The cylindrical shell is a schedule 20 12in pipe. Its outside diameter is 12.75in and its wall thickness is 0.25in. The bottom plate is 1.25in thick and is welded to the shell. It has a 4in penetration 3in away from the centerline for the inlet pipe. The inlet pipe is a schedule 40 4in pipe with an outside diameter of 4.5in and wall thickness of 0.237in. Inside the calibration tank 2.5 inches above the inlet opening a semicircular plate is welded to the

Figure 4. Calibration Tank.

tank wall parallel to the bottom. The plate slows down the inlet flow and protects the level sensors located above it from potential turbulent and violent flow.

The cylindrical shell has one penetration for a gas and overflow. This schedule 40 1in pipe (1.315in OD*0.133in wall) connects the calibration tank to the sump tank and, thus keeps their gas pressures equal. In case of overflow in the calibration tank it also allows the fluid to flow into the sump tank.

The cover has penetrations for instrumentation. There is a 1.5in opening with a 1.5in tube welded to it for thermocouples. It is usually covered with a 0.5in thick blind flange. There are also four level measuring sensor rods that are bolted to the calibration tank cover plate with electrical feed-throughs and extend into the tank.

Figure 5. Expansion Tank.

Calibration will be accomplished by diverting the liquid metal flow from the loop into the calibration tank inlet pipe that connects to the loop

piping after the magnetic flow meter. The level measurement in the tank will be compared to the flow meter reading. When the calibration tank is full, the valve in the inlet pipe will be closed and the drainage pipe will be opened. It drains into the sump tank.

MTL-ET-1   Expansion Tank

The expansion tank is used for liquid lead-bismuth expansion and to contain gas precipitating from the liquid metals. It is located at the highest point in the loop after the 1in test section. It is connected to the horizontal pipe between the test section and the recuperator tube side inlet.

This tank is made of 8in schedule 40 316L pipe. The bottom is a 1in thick plate with a central opening for a 2in schedule 40 inlet pipe. The top is a standard 300lb 8in blind flange bolted to a corresponding slip-on flange that is welded to the tank shell. Internal height of the expansion tank is 19in.

The top flange has a 1/2in outside diameter tube for gas inlet/outlet and four feed-throughs for electrodes serving as level sensors similarly to the other vessels.

MTL-HX-1   Heat Exchanger

The heat exchanger is located just before the flow returns to the sump tank. It decreases the liquid lead-bismuth temperature by 50^0C at the nominal flow speed.

As shown in Figure 6 the heat exchanger consists of two parts: the lower one where the liquid lead-bismuth is cooled, and the upper one where the inlet and outlet pipes for the cooling water are located. The flow of lead bismuth enters at the top of the exchanging volume and leaves the heat exchanger from the bottom pipe.

The heat exchanger is built from several concentric tubes. The loop fluid flows through the annulus between the outer tube and the next largest tube. Annulus created by this tube and the next largest tube is occupied by lead-bismuth that serves as an intermediate fluid and has not connection with the loop working fluid. The inner tube in this annulus is capped and serves as a

Figure 6. Heat Exchanger.

piston that by moving down squeezes the intermediate lead-bismuth up into the annulus thus increasing the heat transfer area and the heat exchanger capacity. The heat is removed by cooling water that flows through the next annulus entering through the upper tube into the innermost tube in the heat exchanger and exiting through the annulus and out of the lower tube. Since two inner tubes have to move vertically in order to change the heat transfer capacity the heat exchanger has a screw mechanism at the top with a handle. Also, sufficient slots are cut out of the outer shell from the water inlet and outlet tubes movement. The junction between the lower and upper part is sealed with two bellows located in series immediately above the flange separating the two parts. They occupy the length of pipe below the water outlet.

The following tube and pipe sizes are used in the lower part of the heat exchanger: 3 1/2in schedule 40, 2 1/2in schedule 40, 2in schedule 40 and a 1 3/4in outside diameter, 0.083in wall tube.

MTL-RC-1   Recuperator
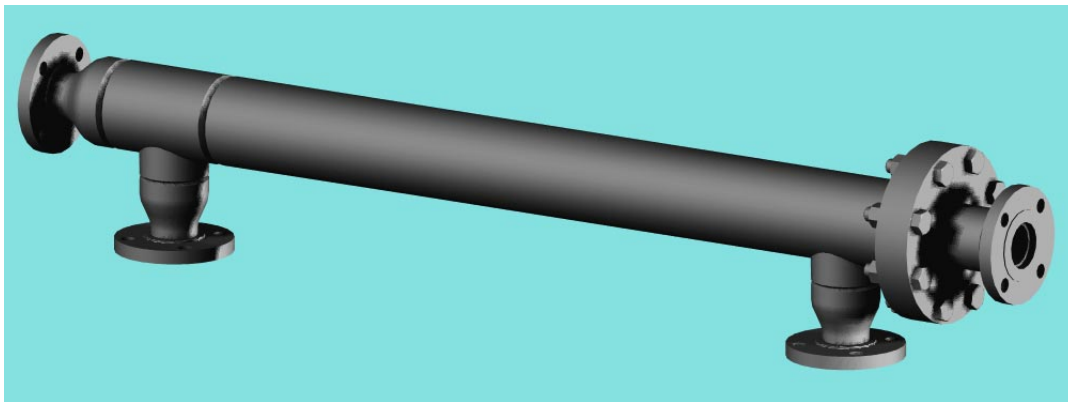
Figure 7. LBE-LBE-water Recuperator.

The recuperator is a standard tube and shell cross-flow heat exchanger. It increases the temperature of liquid lead-bismuth coming out of the sump by heating it up with lead-bismuth that has passed through the heaters located between the shell side and the tube side of the recuperator. Thus, both cold and hot fluids are the liquid lead-bismuth at different temperatures. The "cold" fluid enters shell side through inlet at the bottom shown on Figure 6 on the right. The "hot" fluid enters the tube side through the horizontal inlet shown on Figure 6 on the left. The temperature change is 50^0C at nominal flow speed.

The recuperator is positioned horizontally. Its outer shell is made of 4in schedule 80 pipe and there are 19 tubes inside. The tubes have 0.5625in outside diameters and are arranged in a hexagonal pattern.

MTL-LP-1   Loop

The loop mostly consists of 2in schedule 40 pipe (2.375in OD*0.154in wall). The vertical test section is a schedule 40 1inpipe (1.315in OD*0.133 wall). Five horizontal tubes before the test section, where the heaters are located, are made of a 2in tube (2in OD*0.12in wall). That was done to accommodate the band heaters internal diameters of 2in.

There are sixteen gate valves, one globe valves and three actuated ball valves.

The gate valves have stems that are perpendicular to the pipe. These valves have only two positions: open or closed. They direct the liquid metal flow into the different branches of the loop.

The globe valve is positioned near the sump tank the line that bypasses the loop. This bypass line contains a venturi with a gas injection system for the system clean up.

Both gate and globe valves are made of stainless steel with body and internal parts made of stainless steel 316. These valves are bellows sealed.

The ball valves are pneumatically actuated and computer controlled. Two of the ball valves are the drain valves. These valves are located on the two legs that converge into the last pipe going into the melting tank. They open only when the loop needs to be filled up or drained. They also serve as a safety mechanism. If the valve losses power, it will open and the liquid metal will drain from the loop. The third valve is located on the vertical inlet of the calibration tank. Automatic control of the valve allows to instantly stop fluid flow to the calibration tank when the fluid in the tank reached the necessary level.

The ball valves are made of stainless steel with body and internal parts made of stainless steel 316. Valve seats and seals are made from graphite impregnated stainless steel.

There are bypasses installed in the loop. The first one allows the fluid return to the sump without going through the loop. It also will be used to divert some of the flow from the loop, effectively reducing the flow rate. In addition, the gas cleaning system will be connected the venturi gas

pipe that is in this bypass. The second and third bypasses allows the flow to avoid the shell side and the tube side of the recuperator. The forth bypass is for circumventing the heat exchanger.

The last bypass will be used to return the flow to the heater section without going through the Sump Tank. This "pumpless" loop will be used for natural convection flow, where liquid lead-bismuth will be moved purely by the thermal gradient in the loop.

The heaters are 2in wide bands with 2in internal diameter that fit on the 2in tubes in the loop located essentially below the test section. Each heater provides 750W of power. The heaters will be connected in 9 sections so that the total heating power can be modulated.

There will be a large number of thermocouples on the loop whose reading will be sent to a Data Acquisition and Control system on a computer that will monitor these and other instrument readings in order to collect data and to control temperature, pressure, flow speed, gas input, water flow and etc. in the loop. Other instrumentation on the loop will include gas pressure transducers, fluid pressure transducers, level measuring electrodes, oxygen content meters, a magnetic flow meter and a venturi flow meter.

There are also two blind outlets in the loop. The second test section will be installed and connected to them in the future.

The loop components will be supported from the I beam structure that surrounds the loop (see drawings) using additional steel members, solid supports and spring supports to allow for thermal expansion. There will be a steel drip pan underneath the loop as shown on the isometric drawings.
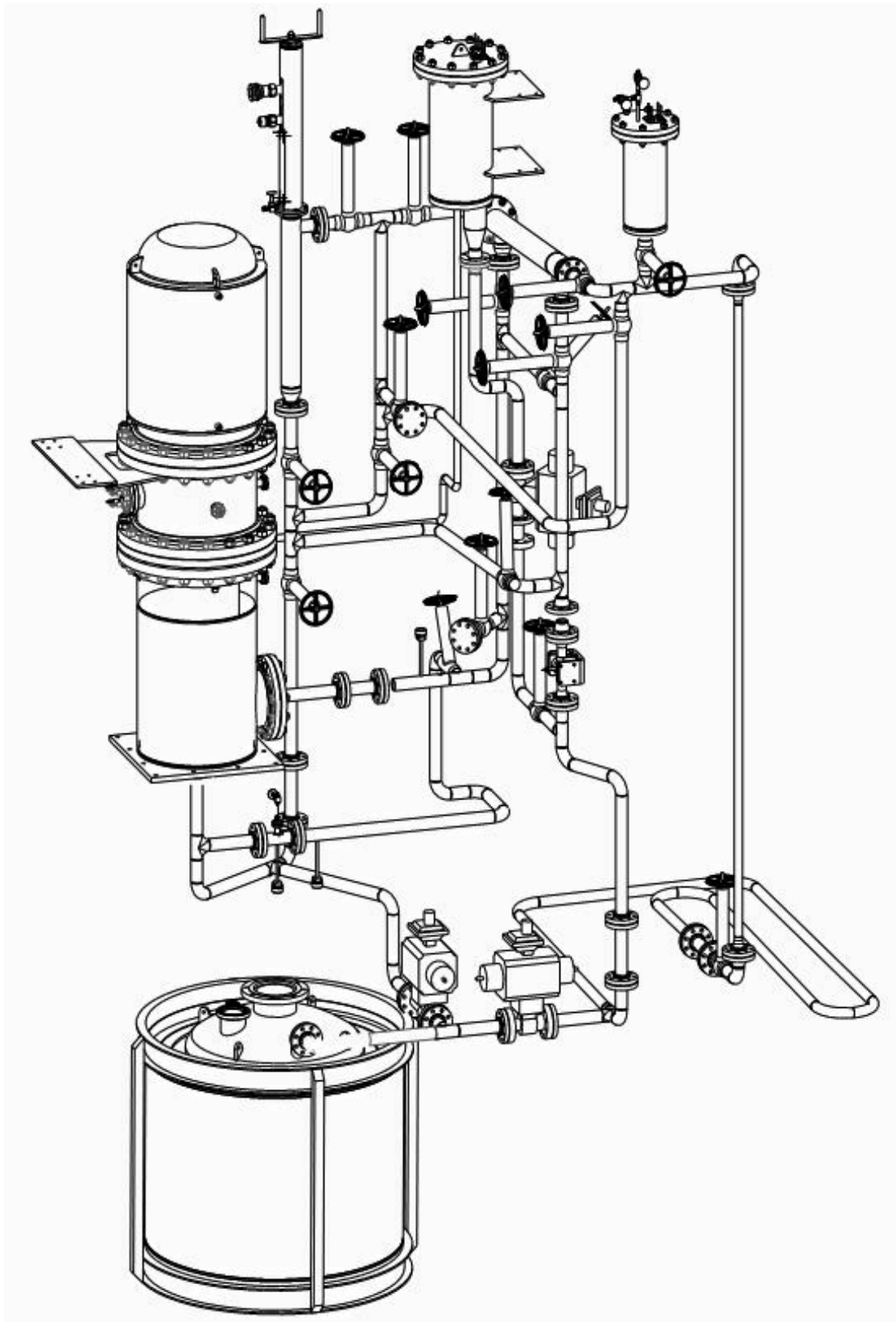
Figure 8. Liquid lead-bismuth loop without the support structure (view 1).
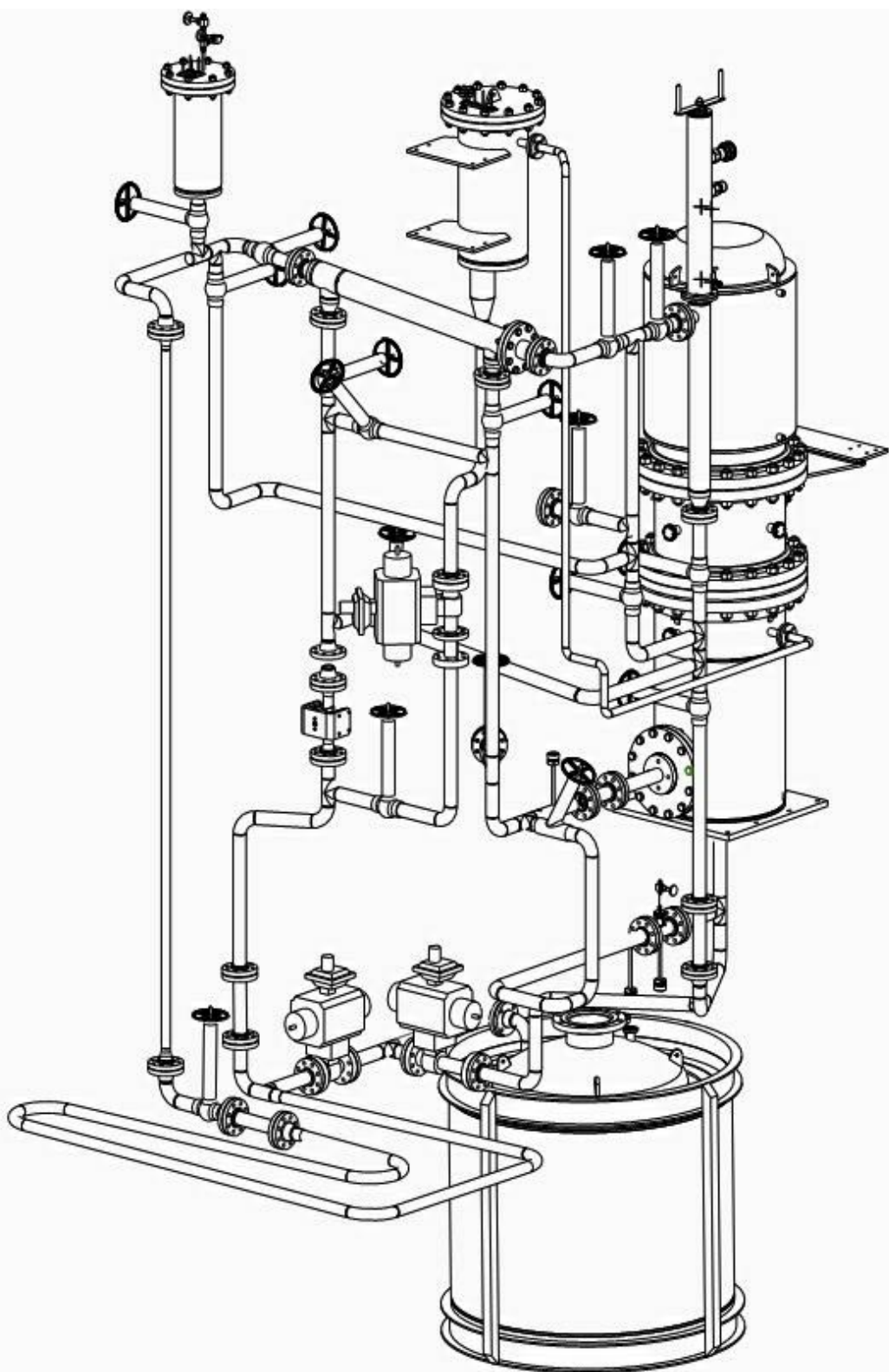
Figure 9. Liquid lead-bismuth loop without the support structure (view 2).

MTL-OC-1   Oxygen Control System

Liquid metals in general are highly reactive and the long term reliability of the loop is to a large extent determined by its resistance to being dissolved, eroded or corroded by the liquid lead bismuth. This resistance is greatly enhanced if a protective layer of oxide exists on the metal surfaces in contact with the liquid lead bismuth. Monitoring such a layer inside the system is difficult, but the oxygen chemistry is sufficiently well known that if the materials are well characterized and we measure the temperature and the concentration of oxygen dissolved in the liquid lead bismuth, we can deduce whether we are increasing, reducing or maintaining the oxide layer. Measurements of oxygen levels in the liquid lead bismuth may be made by measuring the voltage developed across certain ceramics when a difference in oxygen concentration also exists across them. The automobile industry has many years of experience in these ceramics for exhaust line oxygen sensors which we utilize, adapting their sensor elements for our needs. Figure 10 is a drawing of the conical sensor element mounted in the loop.

The construction of the tube (all 316 SS) and the conical shape of the sensor allows it to be replaced by removing the connector flange. We have purchased special sensors from the car industry which allow us to use either another liquid metal (pure Bi) in equilibrium with its own oxide, or porous platinum in contact with air as the reference electrode. The measur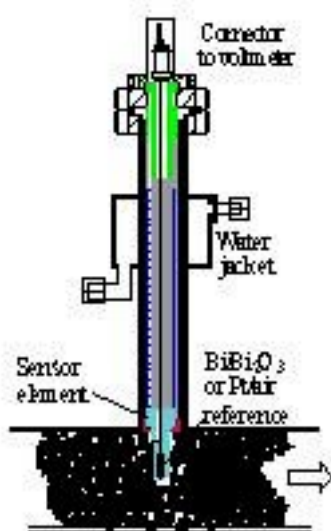ed voltage depends on the ratio of the oxygen concentration in the lead bismuth to that at the reference electrode. Standard coaxial cables will bring the voltage signal from the sensor to high input impedance voltmeters which will send the data to the computer control system. The calculations to convert the voltage to the actual oxygen concentration will be done in the computer, where it will be compared to the levels needed to maintain a good protective oxide layer. The details of the oxide chemistry are covered elsewhere[13].

Figure 10. Oxygen Sensor.

There are four places in the loop where sensors are inserted, corresponding to the hottest and coldest parts of the loop. This is important since the oxidation chemistry varies with the temperature and we need to maintain protection for the entire loop by controlling the oxygen level in the lead bismuth to appropriate levels. This control is a feedback process where oxygen

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[13] N. Li, "Active Control of Oxygen in Molten Lead-Bismuth Eutectic Systems to Prevent Steel Corrosion and Coolant Contamination", LANL technical report, LA-UR-99-4696 (1999), accepted for publication in J. Nuc. Mat.

is added or removed from the liquid by introducing gases into the flow through the cover gas system. Adding hydrogen gas will tend to remove dissolved oxygen from the fluid in the form of water vapor, while adding oxygen gas increases dissolved oxygen.

MTL-DAC-1 Data Acquisition and Control System

Data Acquisition and Control system (DAC) is realized using National Instruments™ data input and output instrumentation and a computer program written LabView, National Instruments™'s graphical data acquisition language.

The user interface has a schematic of the loop Piping and Instrumentation diagram with windows showing the input data and various controls. The input data indicators show the numerical data and/or graphical representation of data such as color bars and gages. The user panel imitates real instruments for its inputs and outputs.

First the program collects the data from the instrumentation on the loop. There are thermocouples, level sensors, pressure transducers, oxygen sensors, flow meters, gas pressure transducers and flow meters. We can also determine the status of actuated valves and the pump motor.

Thermocouples readings are read through four SCXI-1102 32 channel thermocouple amplifiers. The data from the thermocouples is transferred to the computer almost instantly. A panel will be built near the loop enclosure where the thermocouple wires plug into and the other side of the panel connects to SCXI 1102. Using this connection method we can easily change the thermocouples connected to DAC at the loop. 128 thermocouples can be read through these modules. The exact number of thermocouples necessary for operation will be determined from experience.

Levels in the Melt Tank, Sump Tank, Calibration Tank and Expansion Tank are measured with different length metal rods inserted into the vessels. They are attached at the top with electrode feed-throughs that insulate them from the tank. Once liquid lead-bismuth reaches the end of a rod, it closes an electrical circuit between the tank wall and the rod and the voltage applied to the rods produces a current that is read and sent to the DAC program via an analog input module on SCXI 1100 data acquisition chassis.

A magnetic flow meter measures the liquid lead-bismuth flow speed. The liquid metal flows between two parallel permanent magnets and induces an electrical fluid perpendicular to the flow

and to the magnet poles. Thus, two electrodes welded into the wall of the pipe diametrically opposite to each other and located on a line perpendicular to a line between the magnet's poles read a voltage that is proportional to the flow speed. Under the flow meter there is a pipe leading to the Calibration tank. This arrangement allows us to calibrate the flow meter.

There is a venturi in a loop bypass line near the Sump Tank that also allows us to measure fluid low. There is a standard expression relating the pressure measurements from a differential pressure transducer at the venturi and the flow speed. Fluid pressure is also measured in the pipe before he venturi and near the Sump Tank right after the pump outlet.

Gas pressure is measured in the Tanks and in the Heat Exchanger intermediate cover gas.

A special subprogram maintains the oxygen control system. That includes reading the data from six oxygen sensors located on the loop and regulating the cleaning gas injection through an opening in the venturi neck by opening and closing gas valves.

The loop piping is covered with tape heaters. There are also band heaters on the horizontal tubing just before the 1in test section. The vessels are also heated with tape heaters. The melt tank has a its own heater that consists of radiation heater panels arranged around the tank in a cylindrical shape. All of these heaters are controlled from the computer. The regulation in most cases is done by establishing a goal temperature at a control thermocouple on the loop. The program, then, turns the heaters corresponding to this thermocouple on and off to maintain the goal temperature. Portion of the pipe on the screen schematic that represents this heater turns red when it is on and stays unchanged when it is off. The main portion of piping is black other parts are colored differently according to their function: calibration tank inlet is khaki green and bypasses are blue-green. The melt tank heater power can be modulated, so its power is shown on slider indicators with values from 0 to 45kW. The heaters on the other vessels including the heat exchanger and the recuperator are shown as bars that turn red when the heaters are on and blue ahen they are off. They are also regulated by control thermocouples. Heaters are separated into 31 zones plus 20 zones for each of the hand gate valves on the loop and 9 main heating zones for the band heaters. Each heater zone has at least two thermocouples.

The pump speed is controlled through an Allen-Bradly controller that accepts input signal from the DAC system. Pump power and speed can be varied and its value shown on the screen. The pump can also be stopped instantly from the computer user interface.

Three actuated solenoid valves are controlled from the DAC system through a digital on/off module on SCXI-1100. During calibration the Calibration Tank valve closes instantly when the

highest level in the tank is reached. The other two valves are drainage valves and are opened during liquid metal transfer into the loop and drainage. They are linked to the safety subroutines that stop the pump and drain the loop in a variety of emergency and non-emergency conditions. These valves can also be opened by manual controls from the computer.

There is also a total stop button that stops all operations.

DAC system collects all of the input and output data in files for future examination. It also outputs plots of temperature, flow speed, pressure, oxygen content and of any other data desired.

A variety of safety and operational conditions are built into the program. Levels in the tanks are checked, temperatures on the loop, gas and water lines, cover gas pressure, flow speed and others. Warnings, alarms and automatics stops are incorporated into the program according to the nature of discrepancy in the loop.
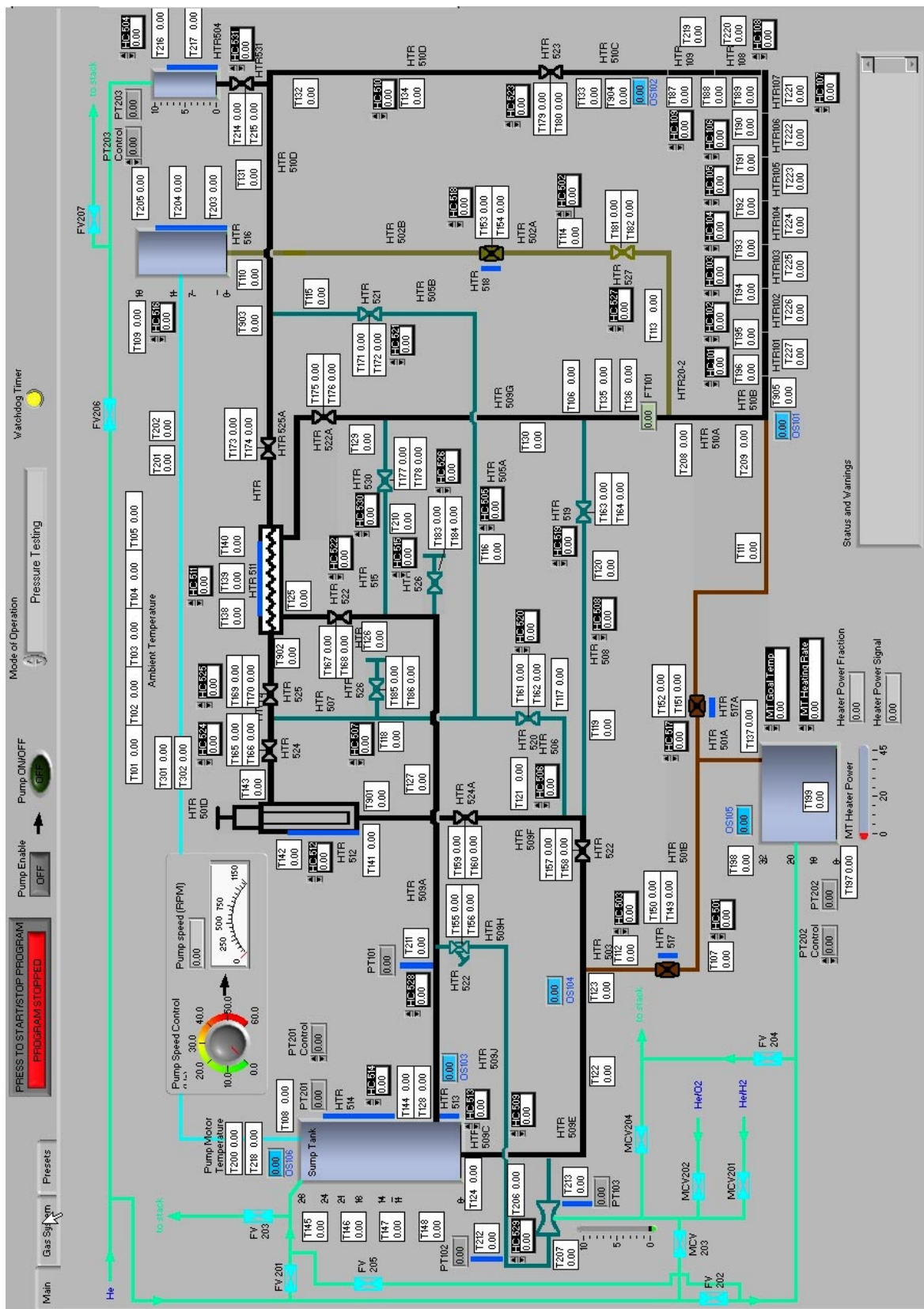
Figure 11. Front panel of DAC software.

MTL-GS-1   Cover Gas System

The helium cover gas is introduced into the sump volume and must be maintained at the pressure needed to support the liquid metal in the higher parts of the loop. The amount of gas required will depend on the particular operating conditions – the flow velocities, pump operating parameters, the amount of gas entrained, or lost by accumulation at the top of the loop, and any other addition of gas, such as for the oxygen concentration control function.

Gas may be added or removed from three locations in the loop: the sump volume, the expansion tank at the highest point, and in a bypass loop where a venturi section has inlet holes for the addition of cleanup and oxygenation gases (He+4%H_2 and He+6%O_2). Pressure control is achieved by computer controlled operation of solenoid valves which will add or remove gas as determined by pressure sensors and liquid level sensors.

The cleanup and oxygen control gas will be isolated from the flow when not in use by a frozen plug of lead bismuth in a special section of the gas line. When gases are added the freeze plug will be melted and forced into the main flow along with bubbles of the gas. Introducing the gas in the high velocity (low pressure) region of the venturi will result in smaller bubbles entrained in the higher pressure regions of the flow. This will produce better mixing and dissolution of the active component of the gas in the lead bismuth.

The control system will compensate for this addition of gas by releasing appropriate amounts from the sump or expansion tank volumes.

MTL-WS-1   Cooling Water System

Cooling water is used in a number of places in the MTL both for heat removal and for the creation of LBE freeze plugs. The primary function of the cooling water is to remove heat from the LBE via the water-to-LBE heat exchanger. The heat exchanger has a dedicated line directly from the building water supply. Instrumentation in this line includes water flow rate and the temperature difference between the heat exchanger inlet and outlet water flows. Water is also circulated in the cooling jacket surrounding the pump motor housing. The purpose of this cooling water is to remove heat from the pump motor. The flow rate of this cooling water is measured with a flow meter.

Cooling water is supplied to each of the four oxygen sensors in the loop. The purpose of this water is twofold: 1) maintain the oxygen sensor electronics within an acceptable temperature

range, and 2) provide cooling for an integral cooling jacket to create an LBE freeze plug in the event that the sensor is damaged. Cooling water is supplied to a cooling jacket on the clean-up gas supply line into the venturi. If the clean-up gas supply pressure should fall below the pressure in the venturi, this cooling water will create an LBE freeze plug to prevent outflow of LBE. Finally, cooling water is supplied to a water jacket on the expansion tank gas input/output line. Should LBE reach the top of the expansion tank, this water will create an LBE freeze plug to prevent outflow of LBE.

MTL-VS-1   Vacuum System

The vacuum system provides a means of removing air (oxygen) from the piping system prior to filling with molten LBE. The system is designed to provide a rough vacuum (~0.1 torr). An initial, reduced-oxygen environment facilitates the oxygen clean-up of the LBE after startup. Two roughing pumps are connected in parallel to the sump tank and melt tank. Exhaust from the vacuum pumps is vented to the building exhaust system through HEPA filters to an exhaust stack.

MTL-ES-1   Exhaust System

The MTL is contained within an enclosure constructed of unistrut covered with aluminum panels. The enclosure is ventilated primarily as a means of heat removal from the air surrounding the MTL. In addition, even though the vapor pressure of lead is extremely low, his ventilation would remove any harmful lead vapors that might be generated.

Air enters the enclosure through a 6"-wide ventilation gap that exists between the floor and the bottom of the aluminum panels. Air exits the enclosure through two exhaust ports that are connected to the building exhaust system. This exhaust air is ducted to the building exhaust stack through HEPA filters. The enclosure exhaust ducts were sized to flow 1600 cfm. This flow rate provides a ventilation rate within the enclosure of one air exchange per minute.

4. TEST AND DOCEMENTATION PLANS

Considering the AAA Program needs for developing a LBE spallation target, and that the radiation damage to the window limits the materials lifetimes, MTL will be first used to demonstrate the safe and predictable operation of a similar-scale LBE system, and not on long-term materials corrosion. The tests will include loop preparation, startup (pump, heaters and heat exchanger), coolant and piping surface conditioning, maintenance of coolant chemistry (measurement and control of oxygen level in LBE), thermal hydraulics measurement (LBE level, temperature, pressure, flow, heat transfer etc) and performance monitoring, off-normal emergency response, and hazard control and mitigation. We will also perform natural convection testing, some partial simulation of spallation product effects (hydrogen injection) and loop restoration (hydrogen sparging) to improve thermal hydraulics.

We will delay the medium to long-duration materials test, but some test coupons will be strategically located in the MTL to survey the results of coolant chemistry control and loop surface conditioning. The National and International collaborations also will be considered in defining the details of the medium- and long-term tests. We will aim at some overlap with parallel efforts for data verification but we will mostly aim at supplementing and complementing the parametric range of the data obtained or planned in other similar test facilities.

The test plan is divided into modules that each operation can be (nearly) independently carried out. In some cases, the test modules may be better carried out in parts and/or combined with the others. This differs from the MTL operating procedures in that only functions and performance goals are prescribed. For actually implementing the tests, refer to the operating procedures[14]. The test modules are arranged in approximately chronological order determined by possible operation feasibility and program needs. The listing here serves as a baseline flow chart for the test operations of MTL.

Since this is an experimental program to learn proper operating procedures and techniques, the test modules, objectives and procedures are subject to change with concurrence of the project management. If the safety parameters are also subject to change, then new HCPs will be generated to mitigate the new hazards.

The processes of the tests, the results, recommended changes and finalized test modules will be recorded for LBE system operations.

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[14] "MTL Operating Procedures", LANL AAA internal report, 2001.

4.1 Near Term Tests (FY01-02)

The following tests are necessary for startup and shake-down operations of MTL. They will be carried out as soon as the construction, assembly and readiness reviews are completed. AAA program priority determined the scheduling priority for MTL test operations.

MTL-T-00   Data Acquisition and Control (DAC) Software

Since it is required and implemented to automate the MTL DAC, it is imperative to test and assure the quality of the software. There is no single test to accomplish this objective so all the test operations will constitute partial DAC software tests. The DAC performance will be recorded and improvement implemented continuously.

MTL-T-01   System Tightness

A. *Vacuum tightness at room temperature:* open all the internal valves in the loop, evacuate the loop with the mechanical vacuum pump to pressure less than 1 torr, stop the pump, then monitor the holding of the vacuum for 2 hours. Repeat the above procedures 4 times, if the loss of vacuum is less than 1 torr in 2 hours, accept and proceed to the next step.
B. *Positive pressure tightness at room temperature:* fill the loop with helium to 50 psia, monitor the pressure for 1 hour, if the loss of the gas is below 5% volume per day (equivalent to pressure loss of 5% per day), accept and proceed to the next test.
C. *Vacuum tightness at a higher temperature:* use the tape heaters to heat up the loop to the maximum achievable temperature, evacuate the loop with the mechanical vacuum pump to pressure less than 1 torr, stop the pump, then monitor the holding of the vacuum for 2 hours. Repeat the above procedures 4 times, if the loss of vacuum is less than 1 torr in 2 hours, accept and proceed to the next step.
D. *Positive pressure tightness at room temperature:* fill the loop with helium to 50 psia, monitor the pressure for 1 hour, if the loss of the gas is below 5% volume per day (equivalent to pressure loss of 5% per day), accept.

Duration: one week
Frequency: initially and after any operations that require opening of the loop

MTL-T-02   Tape Heaters and Loop Preheating without LBE

A. *Tape heater capability:* within the limit of maximum heat up rate of 50ºC/hr, check the actual achievable range from room temperature to 250ºC. With all the tape heaters on, check the maximum preheating temperature without exceeding 450ºC.
B. *Loop preheating uniformity:* with the tape heater distribution, check if the loop can be preheated to a temperature uniformity of 30ºC above 180ºC and below 250ºC within half an hour of each other.
C. *In case of deficiency:* if the tape heaters cannot preheat the loop uniformly, redistribute the heaters, add heaters, or change the thermal insulation and repeat the preceding steps.

Duration: 2 days
Frequency: only initially and after modification of heaters and heating zones

MTL-T-03   Melt LBE in the Melt Tank

A. *Melt tank heater:* at room temperature, close the drain valves, evacuate the melt tank, and flush the melt tank with helium for 5 minutes, then fill the melt tank with helium to 13psia. Within the limit of 50ºC/hr heat up rate, regulate the melt heater to heat the LBE to 180ºC and hold.
B. *Clean the LBE melt* (first time only, subsequent such operations will be determined by oxygen measure and control history): with helium flushing, open the top flange of the melt tank, then use a scoop (fine mesh stainless steel) to clean the slag off the top of the LBE melt till a mirror surface shows (temporarily). For coolant chemistry control, the LBE will need additional oxygen so slight ingress of air and oxidation of LBE is allowable. The cleaning step gets rid of the bulk of the oxides and other non-reducible solid contaminants.
C. *Monitor cover gas oxygen level:* close the top flange after cleaning, heat up the melt to 180ºC and hold. Use the self-heating gas phase oxygen sensor to monitor change in oxygen partial pressure.

Duration: 1 day
Frequency: every time LBE is frozen and needed for a new loop operation (during normal operations, it's desirable to never let LBE freeze or drop below the temperature at which oxides can precipitate)

MTL-T-04   Transfer LBE into the Sump Tank and Loop and Start Circulation

A. *System preparation:* while LBE in the melt tank is held at 180ºC, and the loop preheated to 200ºC, evacuate the loop to less than 1 torr. Open the drain valve at the start of the transfer operation.
B. *Transfer LBE:* gradually increase the helium pressure inside the melt tank to force the LBE melt into the sump tank. Monitor the level rise via the continuity level sensors. Also monitor the temperature changes in the loop as the LBE melt heats up the loop.
C. *Stop transferring:* when the LBE level in the sump tank reaches the needed height, as indicated by the level sensors, shut the drain valves immediately. Monitor the stability of the LBE level and the pressures inside the melt tank and the sump tank (not closing the drain valves soon enough may cause helium to force into the sump tank).
D. *Fill the loop and start the pump:* gradually increase the sump tank helium gas pressure to push the LBE into the sections of the loop above the sump level. Monitor the temperature changes in the loop as LBE fills. It is acceptable to turn on the motor when LBE fills more than 3/4 height of the loop. The circulation of LBE in the loop will be signified by the uniformity of the loop temperature, and a signal from the EM flow meter. Flow induced vibration is not necessarily audible outside the enclosure, but may be monitored through the accelerometers installed on the superstructure and the loop.
E. *Adjust the cover gas pressure:* experience from the first loop operation suggests that when the cover gas pressure inside the sump tank is below certain level, the loop may vibrate and generate excessive noise. By adjusting the pressure up and down slowly, we can determine the pressure vs motor speed curve separating the noisy and quiet operating regimes. Future loop operation will always operate in the quiet regime (without excessive flow induced noise and vibration).

Duration: 2 day
Frequency: every time a new operation is initiated (we will not allow LBE to be left in the loop and freeze; we will only switch between full circulation and calibration runs without draining LBE)

MTL-T-05   SCRAM and Interlock Systems

For safety and system protection, SCRAM and interlock systems are implemented. The effectiveness of such systems will be periodically tested in planned operations.

Duration: 1 day
Frequency: (TBD)

MTL-T-06   EM Flow Meter Calibration

A. *Flow path configuration:* close and open valves for the flow path to go through the EM flow meter into the calibration tank. Close the actuated valve before the calibration tank before the operation.

B. *Loop initial state:* LBE transferred into sump tank, cover gas pressure raised to the "quiet" operating regime, and equilibrated with pressure inside the calibration tank through the connecting gas line.

C. *Start LBE flow:* turn on the motor and temporarily deadhead the pump. Open the actuated valve to allow LBE flowing into the calibration tank, start recording the rise of LBE level inside the calibration tank via the continuity probes and the EM flow meter output.

D. *Stop calibration:* turn off the motor when the LBE level rises to the top level-sensor. Gravity drain the LBE from the calibration tank. Close the actuated valve.

E. *Repeat the above steps for 5 different motor speed within the full range.* Check the flow meter readout against the measured volume flow rate.

F. *Re-calibration:* after certain period of operation, the protective oxide film grown on the pipe surfaces will change the EM flow meter readout (due to change of the contact electrical resistance). This may be observed in significant drift of the EMFM output while the pump motor speed is constant. However, if re-calibration shows more deviation in flow than can be accounted for by the contact resistance change, then the additional change may be due to slag build-up in the loop, esp. in the pump housing and on the impeller.

Duration: 1-2 days
Frequency: as determined by more than 10% shift of the readout at constant pump power

MTL-T-07   Oxygen Measurement, Control and Loop Conditioning

Implementing and improving oxygen control technique to mitigate corrosion and contamination in LBE system is a main technical objective of the MTL. The following test and procedures are derived based on literature and our theoretical understanding. The actual test and conditions may change to achieve the objective.

A. *Loop initial state:* LBE in full circulation in the flow path for corrosion test, bypass loop valve open.

B. *Oxygen sensors:* start monitoring oxygen sensor output as soon as LBE circulation starts. Gradually increase the temperature of LBE by increasing the heating power of the band

heaters to above 350ºC and hold. Observe the oxygen level both in the sump tank cover gas and in LBE at three locations. Compare the sensor output. In time, the partial pressure of oxygen in the gas phase and in LBE should equal each other when there is no solid lead oxide on the melt surface.

C. *Oxygen level:* for conditioning the loop, the oxygen level will be set at 1×10^{-6}wt% at 450ºC ($\log a \sim -2.5$) [15]. Since this is far below the saturation limit at 350ºC, oxygen injection will be performed at this temperature to avoid possible competition between dissolution and oxidation at higher temperatures. During initial operations, the in-LBE oxygen level will be set at about 1×10^{-6}wt%.

D. *Oxygen depletion:* due to the oxidation of the steel surfaces in the loop to form the protective oxide film, the oxygen level in LBE is expected to decrease (if there is little ingress of air). The dynamics of this process is fast at 450ºC at the early stages (according to the Russian experience). The band heater power will be increased to raise the LBE temperature to 450ºC. Monitor the oxygen sensor output. When the oxygen drops below 5×10^{-7}wt%, add oxygen to 1×10^{-6}wt%. This will probably be an operation needed for every 10 – 15 min at the beginning, decreasing to every 30 – 50 min in 20 hours. Actual operation will determine the procedures of preconditioning of the loop surfaces.

Duration: one week

Frequency: after preconditioning, oxygen level needs to be monitored in all operations at all times, and adjusted when necessary (depending on system tightness, may vary from daily to weekly or even longer time intervals)

MTL-T-08   Heat Exchanger (HX) Startup and Setting Temperature Difference

A. *Loop initial state:* LBE in full circulation at the desired mean operating temperature (e.g. 350ºC for the first time), cooling water in HX is blown out initially and subsequently boiled off during the preheating and LBE filling, HX in minimum capacity state.

B. *Turn on cooling water:* monitor the water flow rate, temperature difference between the inlet and outlet, and pressure. There may be some boiling noise initially.

C. *Increase HX capacity:* monitor the mean temperature of LBE loop, gradually increase the HX capacity by raising the handle, while increasing the band heater power. Pause after each step of increasing HX capacity for approximate 5kW (1/10 full capacity), and wait for LBE

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[15] B.A.Shmatko etal. "Corrosion Diagnostics and Technological Process Control by Activity Measurement in Lead-Bismuth Coolant", proceedings of Heavy Liquid Metal Coolants in Nuclear Technology (HLMC-98), Obninsk: SSC RF – IPPE, Vol.1, 694-699 (1999).

mean temperature equilibrate to target temperature. Stop once the desired temperature difference is reached.

D. *HX stability:* operate the HX at the desired temperature and temperature difference for 2 hours while regulating the band heaters, observe temperature stability.

Duration: 2-3 days

Frequency: every operation in which a temperature difference is required

MTL-T-09   Drain LBE and Maintain Coolant Chemistry

A. *Initial state:* LBE in the loop, melt tank is heated to the mean LBE temperature in the loop, helium pressure inside of the melt tank is equilibrated to the sump pressure by opening a connecting valve.

B. *Drain LBE:* open the drain valves, gravity drain the LBE into the melt tank.

C. *Coolant chemistry:* since the oxygen level set during the operation is higher than the solubility limit at certain lower LBE temperature, gradual precipitation of lead oxide on the top surface and increase of oxygen partial pressure will occur if the LBE in the melt tank is allowed to cooled down to below that temperature. Monitor oxygen change via the gas phase oxygen sensor. Ideally we'd like to keep the melt temperature high all the time so oxide won't precipitate and accumulate over time. In the case of setting the oxygen level in LBE at below 0.05 wppm, the melt should be kept at above $250^{o}C$, If the melt is cooled to below the saturation temperature, we'll need to add more oxygen the next time we fill the loop.

Duration: 1 day

Frequency: every time an operation stops, a new loop configuration is required and inspection, maintenance and repair work is needed inside the enclosure

MTL-T-10   Exterior Surveillance of Loop

A. *Bolts:* Bolts holding the flanges together are subject to stress and thermal cycling fatigue. Because the gasket material (graphite-based) will not restore after compression, the bolts (hence gasket seals) may lose tightness after thermal cycling. We need to develop a schedule and a set of criteria to check the bolts.

B. *Flange:* Some of them can be subject to very high design thermal stresses approaching their capacity. They should be checked together with the bolts.

C. *Cooling water:* Check for signs of leakage. Unimpeded flow of cooling water through some components are important to MTL operation so signs of blockage should be checked with the pressure sensors and flow meters embedded in the system.
D. *Contamination:* There are several kinds of leakage from the loop that may occur – leakage of LBE melt through seals and/or cracks, leakage of oxides or vapors from the gas space seals and filters. Visual inspection should be performed frequently. Excessive pressure loss in the cover gas may signal leakage and should be monitored carefully. In case of release of oxides and vapors from the loop, there may be signs of black (or other colors) and/or metallic powder coating near gas space seals. Initially, there shall be a scheduled swiping and air monitoring service performed by ES&H.

Duration: 1 day
Frequency: (TBD)

MTL-T-11   Natural Convection in the Loop

A. *Configuration:* Using the valves to bypass the sump pump, the oxygen-control bypass and the return side of the recuperator to set up the natural convection loop.
B. *Temperature difference and flow velocity*: Set up at least 5 temperature differences from 20 to 100ºC (or higher if thermal stresses in the loop allow) with the heaters and HX. Measure the steady state flow velocities with the EM flow meter.
C. *Transients:* Once we learn to reliably set up the heaters and HX for establishing natural convection, we will study the various on and off transients by recording the temperature and velocity changes in time. This information may be very important in accident scenarios for LBE system in general and spallation targets in particular.

Duration: 2 weeks
Frequency: (TBD)

4.2 Medium Term Tests (FY02)

These tests are important for sustained operation of spallation target like LBE systems. Due to radiation damage imposed lifetime limits on target active area structures, long-term materials performance is not critical at this stage of development. However, due to the accelerated change of coolant chemistry in spallation targets, some additional operations to maintain oxygen control and restore coolant chemistry might be necessary and will be tested.

MTL-T-12   Interior Surveillance of Loop

A. *Test sections:* Several test sections, ones at the highest, the middle and the lowest temperatures in the loop are removable – simple straight piping attached with flanges. They can be removed and visually inspected for signs of corrosion, e.g. pitting and other forms of localized corrosion, excessive oxidation and/or precipitation accumulation.
B. *Coupons:* Inside the test sections, small removable coupons may be mounted on side walls so that more detailed analysis can be performed to monitor the thickness, microstructure and compositions of the oxides, micro-hardness, and other relevant properties.

Duration: 1 week for removing the reinstalling the test sections and coupons
Frequency: (TBD)

MTL-T-13   Oxygen Sensor Design Improvement

A. *Installation and replacement:* The oxygen sensors are now assembled into the external sheath welded into the loop. This facilitates ease of replacement but may compromise leak tightness.
B. *Protection of the active ceramic part:* The ceramic cone of an oxygen sensor is inserted into the mid-stream of the LBE flow in the loop. Adding some protective sheath may enhance the survivability of the sensor but may complicate or even cause spurious readings by having crevices for accumulating oxide contamination.
C. *Ceramic cone vs disc for the sensor:* The ceramic cones in our current prototypes offer fairly good mechanical and thermal stability and are easy to seal. However, the large active area may also contribute to complications in readouts. Using discs and ceramic to ceramic and/or metal seals are more difficult for fabrication and assembly but may provide a simpler and easy to maintain active surface for enhanced signal reliability.

Duration: ongoing

MTL-T-14   Gas phase oxygen control and oxygen sensor calibration

A. *Hydrogen/water steam mixtures:* The oxygen partial pressure in an oxygen-controlled LBE system is very low ($< 10^{-26}$ atm). Using direct gas injection and measuring the oxygen activity with the oxygen sensor is one way to achieve control. The other method, lending

itself nicely to cross calibration of oxygen sensors with absolute oxygen partial pressure, is to use hydrogen and steam mixture[16]. A hydrogen and water steam mixture, covering from ferrous oxide (magnetite) dissociation (lower limit of oxygen level) to oxygen saturation in LBE (higher limit) will be adiabatically changed for LBE to reach equilibrium with the cover gas. Inferred oxygen partial pressure will be used to calibrate in-LBE oxygen sensors.

B. *Gas chromatography:* This can be used to measure the hydrogen and water steam composition in the cover gas directly.

C. *Cross calibration of gas/liquid phase oxygen sensors:* Gas-phase oxygen sensors, widely used (e.g. in automobiles), are well understood, calibrated, and can be heated to high enough temperature to measure the oxygen levels in the cover gas. The readout can be used to cross calibrate the in-LBE oxygen sensors. Calibrated oxygen sensors in gas phase and in LBE can also be used to study the equilibration processes between the two phases.

Duration: ~ 1 month
Frequency: (TBD)

MTL-T-15   Solid Mass Exchanger for Oxygen Control

The gas phase oxygen control may not be optimal since gas-liquid mass exchange is usually not the most efficient. Using solid lead and/or bismuth oxides in a mass exchanger located in a bypass loop that can be open or closed may be more effective[17]. Design and implementation of such control system will be evaluated. If it's determined to be superior, it will be implemented and tested.

Duration: ~ 1 month

MTL-T-16   Filters and Magnetic Trap(s) for Solid Contaminants

Ferrous solid oxides may form and precipitate out of LBE in MTL. Deposit of the oxides may degrade performance of thermal hydraulics (e.g. blockage of flow, slag formation on pump impellor to reduce pumping capacity, etc) and heat transfer (e.g. lower HX and recuperator capacity). These contaminants may be captured by filters, or by magnetic traps. If strategically

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[16] N. Li, "Active Control of Oxygen in Molten Lead-Bismuth Eutectic Systems to Prevent Steel Corrosion and Coolant Contamination", LANL technical report, LA-UR-99-4696 (1999), accepted for publication in J. Nuc. Mat.

[17] P.N. Martynov, Yu.I. Orlov, "Slagging Processes in Lead-Bismuth Loop. Prevention and Elimination of Critical Situation", in proceedings of HLMC-98, Obninsk, Russia (1999).

located magnetic traps can reduce solid contaminants that are not chemically reducible, we may not need to develop filters for long-term MTL operations.

A. *Filters*: We'll evaluate the need for filters after some initial operation and interior surveillance.
B. *Test sections with external magnets:* Since the test sections are easily removable for observation and restoration, we will place U-shaped magnets around the entrance to try to collect ferrous solid contaminant. Appropriate methods (TBD) will be used to measure the effectiveness of such magnetic traps.
C. *EMFM inspection:* Since the EMFM is a natural magnetic trap and operates in the loop at all times, examine the effectiveness by periodically removing it from the loop will be useful. In addition, restoration may be necessary if too much precipitation/collection takes place and affects the flow meter performance.

Duration: 3 weeks
Frequency: (TBD)

MTL-T-17   Coolant Chemical Analysis

A. *Impurity changes:* Coolant impurities will change over time due to accumulation of some corrosion products, and the application of oxygen control (e.g. preferentially oxidizes some impurities and volatize them).
B. *Corrosion products:* corrosion products may be dissolved or dispersed in LBE. Coolant sample analysis will reveal the levels of corrosion products.

Duration: 2 weeks
Frequency: (TBD)

MTL-T-18   Partial Simulation of Spallation Product(s)

A. *Inject hydrogen:* Hydrogen may be injected at a rate commensurate to 1-MW LBE target production rate to simulate part of the spallation product effects on oxygen control. Several effects may be expected and monitored. The immediate reaction is the depletion of oxygen in LBE and this will be registered by the oxygen sensors. We may simulate the target operation by injecting additional oxygen to adjust the oxygen activity, or simulate failure to control oxygen level and observe the change in corrosion behaviors.

4.3 Long Term Tests (FY02 and beyond)

Once we can reliably operate MTL with oxygen control, we can shift our attention to long-term materials performance tests, system and sensor performance improvement, modification and development of more corrosion resistant alloys, and systematic investigation of system corrosion behaviors with modeling support.

MTL-T-19   Materials Corrosion Testing

Medium to long duration materials corrosion testing in MTL can help resolve many critical issues. Chief of them are the proper oxygen control regimes for optimal materials performance, optimal impurity levels in alloys for highly protective and easily restorative surface oxides, and onset of erosion and erosion/corrosion.

MTL-T-20   Active Online Corrosion Probes Development and Testing

Corrosion sensor development will exploit the dielectric properties of the oxide film that forms on metals during the corrosion process to generate corrosion data (such as rate). During oxide growth (i.e. formation of a protective layer and corrosion) oxide ions are transported from the oxide | environment interface through the porous and barrier layers to the metal | barrier layer interface where they are consumed while metal ions move in the opposite direction. The resulting change in dielectric properties of the oxide film may be measured by applying a small amplitude sinusoidal voltage perturbation across the oxide | environment interface. We will develop a corrosion sensor based on a method for this measurement to provide real-time kinetic information about the corrosion process such as rate and mechanism, and monitor the integrity of the protective films. This probe would be sensitive to changes in coolant chemistry, such as oxygen concentration, temperature and flow, and material type. The mechanistic information provided by the sensor technology will be used to evaluate and test potential alloy modifications to mitigate corrosion in LM coolant systems.

MTL-T-21   Oxygen Sensor Improvement and Lifetime Testing

A. *Thermal cycling:* This may be a limiting factor to the oxygen sensor's lifetime since the ceramic part and its joint with metallic housing may be vulnerable to thermal cycling stress.

B. *Replacement and Restoration:* After long periods of operations, the active part of the sensor (the ceramics) may be fouled or covered with contaminants, and may develop cracks or compromised seals.

C. *Systematic calibration:* This is aimed at producing oxygen sensors that are calibrated with absolute oxygen partial pressures, cross calibrated with the gas phase sensors and different types (e.g. different reference electrodes), and oxygen solubility limit and protective oxide dissociation limits. The oxygen sensors can be used in prototype spallation targets and other LBE systems.

MTL-T-22   Hydrogen Injection and Loop Restoration

A. *Oxygen sensor responses:* High level of hydrogen in LBE will affect the oxygen sensors.

B. *Test sections and coupons examination:* The performance of hydrogen sparging to restore the loop (by chemically reducing the precipitated oxides) can be analyzed with the coupons in the test sections.

C. *Heat exchanger and recuperator performance change:* Accumulation of precipitated oxides or other contaminants on the heat transfer surfaces of the HX and recuperator can be measured over time.

MTL-T-23   System Corrosion Dynamics Study

A kinetic model was developed to estimate the corrosion/precipitation rate in a non-isothermal liquid lead-bismuth eutectic (LBE) flow loop[18]. The model was based on solving the mass transport equation with the assumptions that convective transport dominates in the longitudinal flow direction and diffusion dominates in the transverse direction, and that no significant oxide formation and precipitation from the corrosion products in LBE flow. The species concentration at wall is assumed to be determined either by the solubility of species in LBE in the absence of oxygen or by the reduction reaction of the protective oxide film when active oxygen control is applied. Analyses show that the corrosion/precipitation rate depends on the flow velocity, the species diffusion rate, the oxygen concentration in LBE, as well as the temperature distribution along a loop. Active oxygen control can significantly reduce the corrosion/precipitation of the

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[18] X. Y. He, N. Li, A. Smith and M. Mineev, "A Kinetic Model for Corrosion and Precipitation in Non-isothermal LBE Flow Loop", J. Nuc. Mat. 297 (2001) 214-219.

structural materials. It is shown that the highest corrosion/precipitation does not necessarily locate at places with the highest/lowest temperature. For a simplified MTL model, the highest corrosion is predicted to occur at the end of the heater zone, while the highest precipitation occurs in the return flow in the recuperator.

4.4. Documentation of Tests and Results

All design documents (drawings, P&ID etc) shall be archived. All materials and parts certifications, test reports of fabricated components and welds, and other relevant information shall be collected (to the extent that they are available) and filed. All engineering calculation and analysis shall be annotated (calc-note) and archived according to the AAA Program requirements.

All tests and test results must be recorded at the time of performance and archived subsequently. These documents shall reference the test matrix outlined here. New tests, as the needs emerge during MTL operation and AAA Program development, shall be appended to this test plan. The test plan, with the first Program approved version as 1.0, shall be updated to reflect the changes.

5. FACILITY DESCRIPTION AND HAZARD CONTROL

5.1 Facility

MTL is located in the high-bay area of MPF-18, TA-53 (see Figure 12 and Figure 13). It is surrounded with a fence that has three gates – two from the building general area and one from our laboratory. The first LBE hydraulic test loop is also fenced in the same area.

Figure 12. MTL (near completion) located in MPF-18, TA-53.

Figure 13. MTL station (DAC center, instrumentation and power panels, platform and interlocked metal enclosure).

The power supply, ventilation ducts, water and gas lines have all been brought into the fenced area for MTL.

5.2 Hazard Control Plan (HCP)

A separate HCP document[19] analyzes the hazards, list the relevant policies and requirements, and detail the mitigation steps in the design, engineering and operation of the MTL.

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[19] "Hazard Control Plan", Activity # LANSCE-3 HCP-01-012, internal LANL document (2001).